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STATUS OF TRISO FUEL IRRADIATIONS IN THE ADVANCED TEST REACTOR SUPPORTING HIGH-TEMPERATURE GAS-COOLED REACTOR DESIGNS

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Abstract – *The Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is irradiating up to seven experiments on low-enriched uranium tristructural isotropic (TRISO) particle fuel. Irradiations and fuel development are being accomplished at Idaho National Laboratory's Advanced Test Reactor to support development of the next generation of reactors in the United States. The experiments are being irradiated over several years to demonstrate and qualify new TRISO-coated particle fuel for use in high-temperature gas reactors, with goals of providing irradiation performance data to support fuel process development, qualifying fuel for normal operating conditions, supporting development and validation of fuel performance and fission product transport models and codes, and providing irradiated fuel and materials for post-irradiation examination and safety testing. The experiments are irradiated in an inert sweep gas atmosphere, with individual online temperature monitoring and control of each capsule and online fission product monitoring of effluent to track individual capsule fuel performance.*

The first experiment (AGR-1) started irradiation in December 2006 and was completed in November 2009. The second experiment (AGR-2) started irradiation in June 2010 and completed in October 2013. The third and fourth experiments have been combined into a single experiment (AGR-3/4), which started its irradiation in December 2011 and completed in April 2014. Because the purpose of this experiment was to provide data on fission product migration and retention in the next generation reactor, the design of this experiment was significantly different from the first two experiments. The final experiment (AGR-5/6/7) is scheduled to begin irradiation in early summer 2017.

I. INTRODUCTION

Fuel development and irradiations are being performed to support development of the next generation of reactors in the United States. The Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will complete the irradiation experiments over the next 4 to 5 years to demonstrate and qualify new low-enriched uranium (LEU) tristructural isotropic (TRISO) particle fuel for use in high-temperature gas-cooled reactors (HTGRs). Goals of the irradiation experiments include providing irradiation performance data to support fuel process development, qualifying fuel for normal operating conditions, supporting development and validation of fuel performance and fission product transport models and codes, and providing irradiated fuel and materials for post-irradiation examination (PIE) and safety testing.[1] Each experiment consists of multiple separate capsules and will be irradiated in an inert sweep gas atmosphere with individual online temperature monitoring and control of each capsule. The sweep gas will also have effluent online fission product monitoring to track fuel performance in each individual capsule during irradiation.

The experiments are specially designed for an exact irradiation position (e.g., location and size) and specific irradiation parameters (e.g., temperature and fluence). The experiments employ an umbilical tube for housing and protecting the instrumentation and gas lines, including from the individual capsules to the monitoring, control, and data collection system connections at the reactor vessel wall. The overall design concept and sweep gas systems used to control capsule temperatures and monitor for fission gas release will be common to all AGR fuel experiments. However, the experiment capsule design, which was identical for the first two experiments (i.e., AGR-1 and AGR-2), was extensively modified for the third irradiation, which is a combination of the third and fourth experiments (designated AGR-3/4). The test train modification was performed primarily to support the specific purpose of the third irradiation; however, it was also done to accommodate the different types of irradiation positions (e.g., flux trap versus large B) to be used. The final test train in this campaign, designated AGR-5/6/7, is currently being fabricated. This paper will discuss its mission, design, and support systems. Background information relative to the AGR irradiations in general was previously presented in reference 5 and has been reproduced herein in the interest of completeness

II. EXPERIMENT DESCRIPTION AND MISSION

AGR-5/6/7 is an instrumented lead-type experiment with online active temperature control and fission product monitoring of the effluent gas. The other major types of irradiation experiments commonly performed in the Advanced Test Reactor (ATR) are pressurized water loop experiments and static capsule experiments. The pressurized water loop experiments also have active monitoring and control systems, but the static capsule experiments have only passive monitoring and control; therefore, experimental results are determined after irradiation by examination in a hot cell.

The overall concept for temperature control of experiment capsules, temperature control system design, and fission product monitoring system design are all essentially identical to those used on AGR-1 and AGR-2. The experiment capsules utilize an insulating gas jacket with variable mixing of helium and neon sweep gases to control temperature of the fuel during irradiation. New gas temperature control and fission product monitoring systems were installed for AGR-3/4 because the existing systems were being used to irradiate AGR-2 in parallel with the AGR-3/4 irradiation. The new systems are essentially duplicates of the previous systems. Because AGR-3/4 was a combination of the third and fourth experiments, the new system required twice as many temperature control channels and fission product monitors as the previous systems used for irradiation of AGR-1 and AGR-2.

The primary mission for AGR-5/6/7 is to support fuel qualification for the Nuclear Regulatory Commission (NRC), accomplish fuel margin testing (AGR-7), and prove industrial scale fuel fabrication capabilities. The purpose of the margin test is to demonstrate that there is a margin between the highest fuel temperature in an operating high temperature gas reactor (HTGR) and the temperature at which fuel particle failure rates become unacceptable. Like AGR-3/4, AGR-5/6/7 will be irradiated in the northeast flux trap (NEFT) position in ATR, which is in contrast to the Large B positions used to irradiate AGR-1 (B-10) and AGR-2 (B-12). These different irradiation positions are shown in Figure 1.

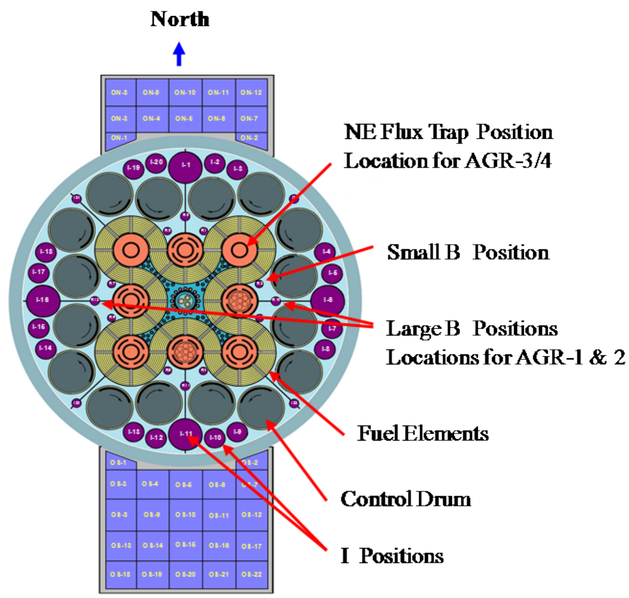

Fig. 1. ATR core cross-section showing the AGR fuel irradiation locations.

The NEFT has higher fast (i.e., 4.4 x 10^{14} versus 2.5 x 10^{14} n/cm^2-s) and thermal (i.e., 1.1 x 10^{14} versus 1.61 x 10^{13} n/cm^2-s) neutron fluxes, which allows irradiations to achieve the burnup and fast fluence requirements in a shorter period of time (i.e., approximately 20 to 24 months versus 30 to 36 months in a Large B position). The increased fast to thermal neutron flux ratio in NEFT also required tailoring of the neutron flux spectrum to prevent exceeding the maximum fast fluence limit before the fuel burnup goals were achieved. However, the acceleration factor between these ATR experiments and HTGR for fuel burnup and fast neutron fluence accumulation will remain at or below three to prevent premature fuel particle failures. Because the NEFT position is almost four times the diameter of the Large B positions, AGR-3/4 and AGR-5/6/7 are much larger in size and different in shape compared to AGR-1 and AGR-2. This much larger diameter irradiation position also supports irradiating two or three experiments simultaneously (as previously planned) by doubling or tripling them up into a single test train. This allows effective use of the larger position to reduce the required irradiation time and obtain the necessary fuel burnup and fast fluence levels as early as practical. The schedule advantage of using the NEFT position is demonstrated in the irradiation schedules for AGR-2 versus AGR-3/4. Irradiation of AGR-2 started in June 2010 and irradiation of AGR-3/4 started approximately 18 months later in December 2011. However, irradiation of AGR-2 completed in October 2013 and completed only 6 months later for AGR-3/4 in April 2014.

The primary functions of the test train are to support the fuel compacts at appropriate elevations in the ATR reactor core, to provide a pressure boundary between the reactor primary coolant and provide an inert gas environment around the compacts, to provide temperature measurements at locations near the fuel, to provide a means of controlling temperature in the fuel compacts, and to tailor the neutron flux environment.

III. FUEL TYPES AND DETAILS

The AGR-5/6/7 fuel is comprised of TRISO-particle fuel in the form of cylindrical compacts. There will be a total of 194 compacts distributed within 5 capsules with a U-235 content of 35.7 grams and total uranium content of 230.3 grams. The compacts will have nominal packing fractions of 25% (inner capsules- near core center) and 40% (outer capsules- at core ends). The particles were made from uranium oxycarbide-type (UCO) LEU fuel kernels with an enrichment level of 15.5%. The individual fuel particles are comprised of fuel kernels that are covered with a layer of silicon carbide sandwiched between two pyrolytic carbon layers to make up the TRISO-coated fuel particles. The fuel particles are over-coated with a mixture of graphite powder and thermo-set resin and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. After being covered with the TRISO coatings, the 425-µm nominal diameter fuel kernels result in approximate 870-µm nominal diameter fuel particles.

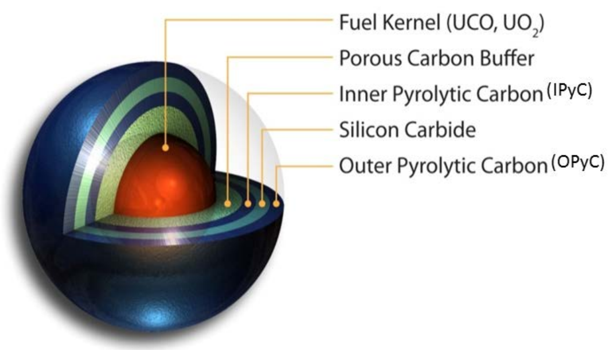

Fig. 2. TRISO Particle

To achieve the desired statistical relevance, the program has determined that AGR-5/6 should contain approximately 500,000 fuel particles and AGR-7 (margin test) should contain approximately 50,000.

IV. IRRADIATION REQUIREMENTS

The 5 capsules in the AGR-5/6/7 experiment will provide data in different combinations of irradiation temperature, fuel burnup, and material types/ configurations. For AGR-5/6, 30% of the particles will operate <900ºC, 30% will operate at 900ºC-1050ºC, 30% will operate at 1050ºC to 1250ºC, and the remaining 10% will operate at 1250ºC to 1350ºC. For the margin test, AGR-7, all 50,000 particles will operate at 1350ºC to 1500ºC. AGR-5/6/7 will utilize the full 1.2-meter active core height in ATR to provide the desired broad range of fuel burn-up and temperature combinations. The initial fuel compact burnup goals were a minimum of 6% fissions per initial metal atom (FIMA) and a maximum of 18% FIMA.

V. EXPERIMENT CAPSULE DESIGN

The overall concept for the AGR experiment capsules is very similar for all irradiations. However, design of the experiment capsule, which was essentially identical for the first two irradiations (AGR-1 and AGR-2), was significantly modified for AGR-3/4. The change was needed primarily to support the different mission and purpose of AGR-3/4 and to accommodate the new type of irradiation position that will be utilized. As indicated earlier, the AGR-3/4 irradiation was performed in the much larger NEFT irradiation position in ATR to reduce the overall irradiation schedule of the AGR experiments. AGR-5/6/7 will reuse AGR-3/4 design concepts as much as practicable. A horizontal cross-section of the AGR-5/6/7 experiment capsules is shown in figures 3 through 5.

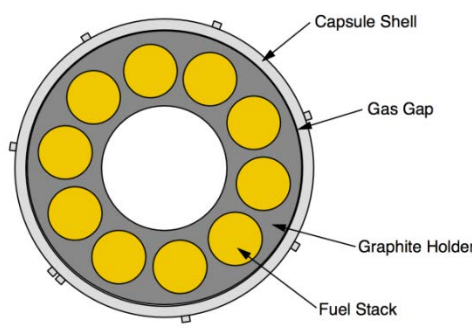

Fig. 3. AGR-5/6/7 capsule 1 cross-section.

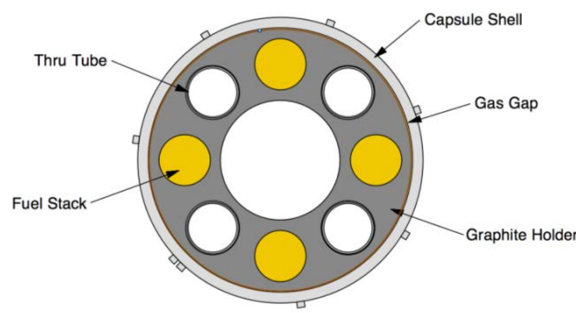

Fig. 4. AGR-5/6/7 capsules 2, 4, 5 cross-sections

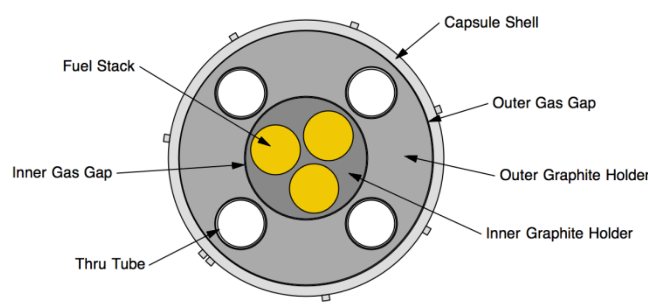

Fig. 5. AGR-5/6/7 capsule 3 cross-section

Capsule 1 (bottom capsule in test train), contains ten fuel stacks (90 compacts), a hollow center to reduce total energy deposition, is nine inches long, and has no through tubes. With no through tubes there is more room for fuel stacks and, therefore, capsule 1 contains the most fuel (60%) of the AGR-5/6 capsules and is also the hottest. The purpose of the through tubes is to allow gas lines and instrumentation from lower capsules to be passed up and out of the test train. This means that the capsules are not completely sealed off from one another, but since there is no need for through tubes in capsule 1 it is completely sealed (no cross-talk between capsules). Since instrumentation lines are degraded by high temperatures, it makes sense to make capsule 1 the hottest of the AGR-5/6 capsules.

Capsules 2, 4, and 5 have four fuel stacks each and, like capsule 1, contains hollow centers. Capsule 2 contains 32 compacts and is eight inches in length, capsules 4 and 5 each contain 24 compacts and are six inches in length.

Capsule 3 (AGR-7 margin test) contains three fuel stacks consisting of 24 compacts and is eight inches in length. It also contains a unique design feature in that the graphite holder has been separated into two pieces, depicted by the two shades of gray in figure 5, allowing the center mass to run hot while keeping the through tubes relatively cool, thereby extending the life of the instrumentation lines contained within the through tubes.

In preparation for assembling the capsules, a substantial effort was undertaken to perform brazing trials for several reasons. First, the operator that performed brazing on AGR-3/4 took another position in the company and is unavailable to conduct the AGR-5/6/7 brazes. Second, there are differences in the design of AGR-5/6/7 capsule heads that make brazing more difficult, including a center penetration, which had not been done before. Third, niobium, a refractory metal, will be used to penetrate the stainless steel capsule heads. Refractory metals have historically been more difficult to successfully join to stainless steel by brazing.

These brazing trials proved to be invaluable in that a good filler material was identified that would not remelt at the capsule head operating temperatures while also successfully joining the refractory metal to the stainless steel head. The most important factor in obtaining successful brazes was maintaining an oxygen free environment. This was achieved by ensuring that all cleaning fluids had been removed from the parts prior to brazing and maintaining a positive helium pressure in the quartz tube throughout the purging and brazing process.

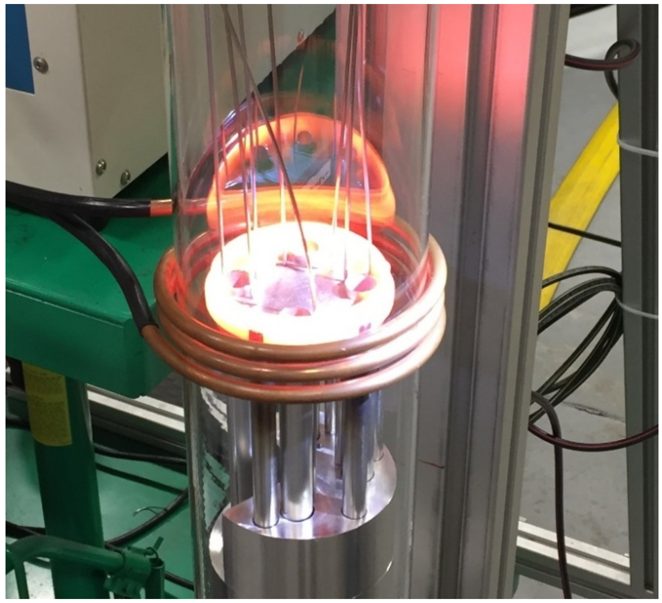

Fig. 6. Brazing process

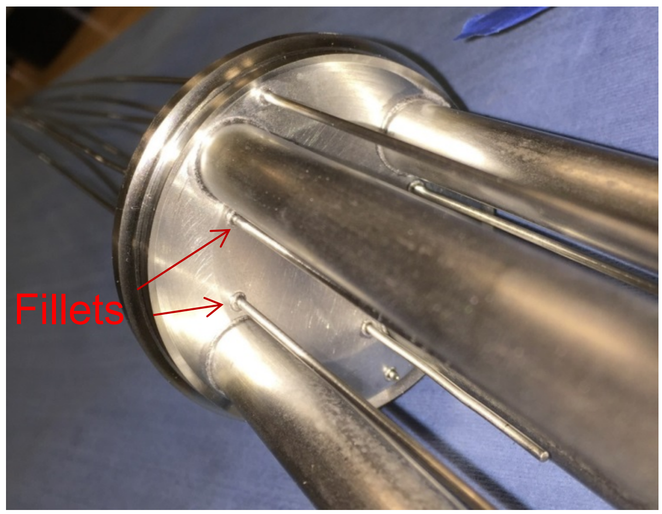

Fig. 7. Brazing complete

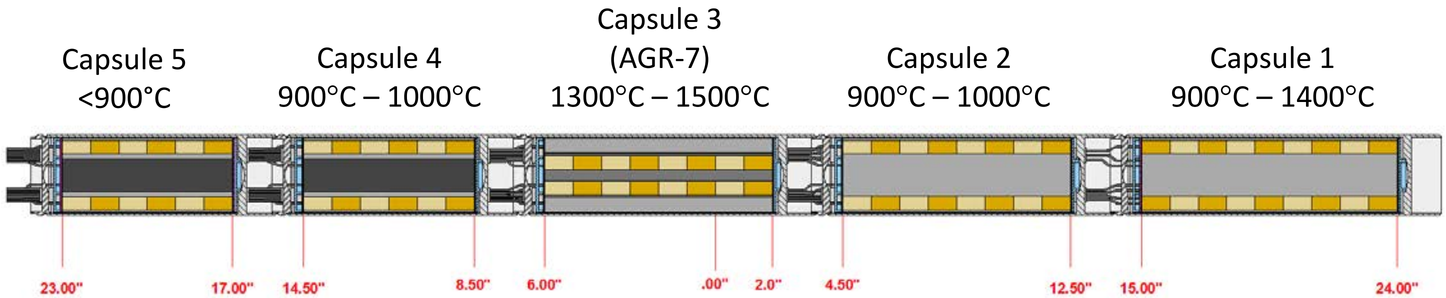

Fig. 8. AGR-5/6/7 test train in-core section

VI. TEST TRAIN DESIGN

The AGR-5/6/7 experiment test train will be very similar to AGR-3/4 with five separate stacked capsules welded together to form the core section of the test train. The plenum regions between capsules have been extended over previous designs to accommodate the bending of larger and stiffer thermocouples. The core section is welded to an umbilical tube (i.e., termed a leadout at ATR) that houses and protects the gas lines and thermocouple leads. The leadout is routed from the NEFT position straight up from the ATR core to the experiment penetration in the reactor vessel top head. Above the vessel top head, the gas lines and thermocouple leads are connected to their facility counterparts in the temperature monitoring, control, and data collection systems similar to the other AGR experiments. The leadout also vertically located the experiment within the NEFT (shown in Figure 1) in the ATR core. A section of the AGR-5/6/7 test train is shown in Figure 8.

To maximize the available irradiation space and meet the fluence and burnup requirements, a new flux trap irradiation housing was designed and is shown in Figure 9. The irradiation housing interfaces with the ATR core structure that supports the ATR fuel elements surrounding NEFT; the housing also locates the test train in the center of NEFT. The neutron flux is moderated to reduce the fast-to-thermal neutron flux ratio to prevent excessive fast neutron damage while achieving the desired fuel burnup. The housing also helped lower the overall thermal neutron flux rate to keep the irradiation acceleration factor to less than three and prevent possible premature fuel particle failures. Furthermore, NEFT is the primary irradiation position within the northeast quadrant of ATR and its power level is controlled by the four control drums (see Figure 1) on its north and east sides. The irradiation program using NEFT has the ability to determine the power level (within specified limits) in the northeast quadrant, which was a very key parameter in limiting the irradiation acceleration factor. Controlling the power level was also crucial in maintaining a relative flat heat generation rate within the AGR-5/6/74 fuel compacts to achieve the constant desired irradiation temperatures during the experiment.

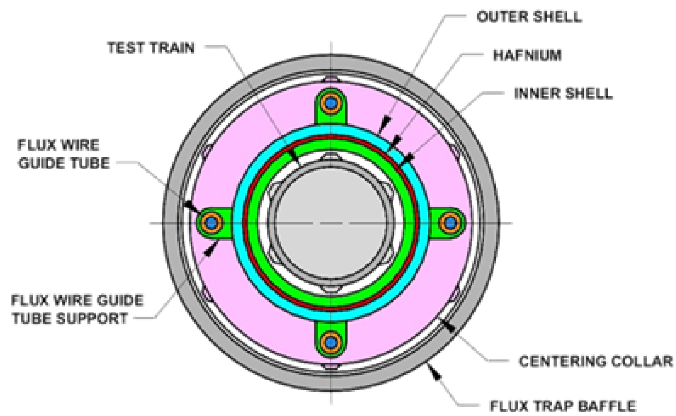

Fig. 9. AGR-3/4 and 5/6/7 irradiation housing cross-section.

The irradiation housing for AGR-3/4 consisted of inner and outer stainless steel shells with a hafnium filter sandwiched between them. The outer shell had centering collars with spacer nubs on them located at the top and bottom of the housing (above and below the active core height of ATR) to provide a uniform reactor coolant channel between it and the ATR core structure. In the same manner, spacer nubs on the AGR-3/4 test train ensured a uniform reactor coolant channel between the test train and the irradiation housing. The center section of the irradiation housing, which is located within the active core height of ATR, contained a very wide coolant channel that is located vertically between the centering collars that are shown in pink in Figure 9. In addition to its cooling function, the reason this water coolant channel was exceptionally wide was to moderate the neutrons coming from the ATR driver fuel and reduce the fast-to-thermal neutron flux ratio. The hafnium filter in the housing next to the test train helped reduce thermal neutron flux and power level adjustments to maintain the low irradiation acceleration factor. Design of the irradiation housing required a very close coordinated effort between its design, the test train design, and the reactor physics and thermal analyses.

The above discussion still holds true for AGR-5/6/7 with an added caveat. Unlike every other test train that the program has produced, AGR-5/6/7 is being designed to stay in the reactor for high power runs conducted periodically for

Naval Reactor tests. This necessitated the design of additional filters to be changed out based upon the reactor power and the burnup achieved. This will aid in tailoring the fast/thermal spectrum over a much wider operating band. These filters are designated heavy, intermediate, and light. See figure 10.

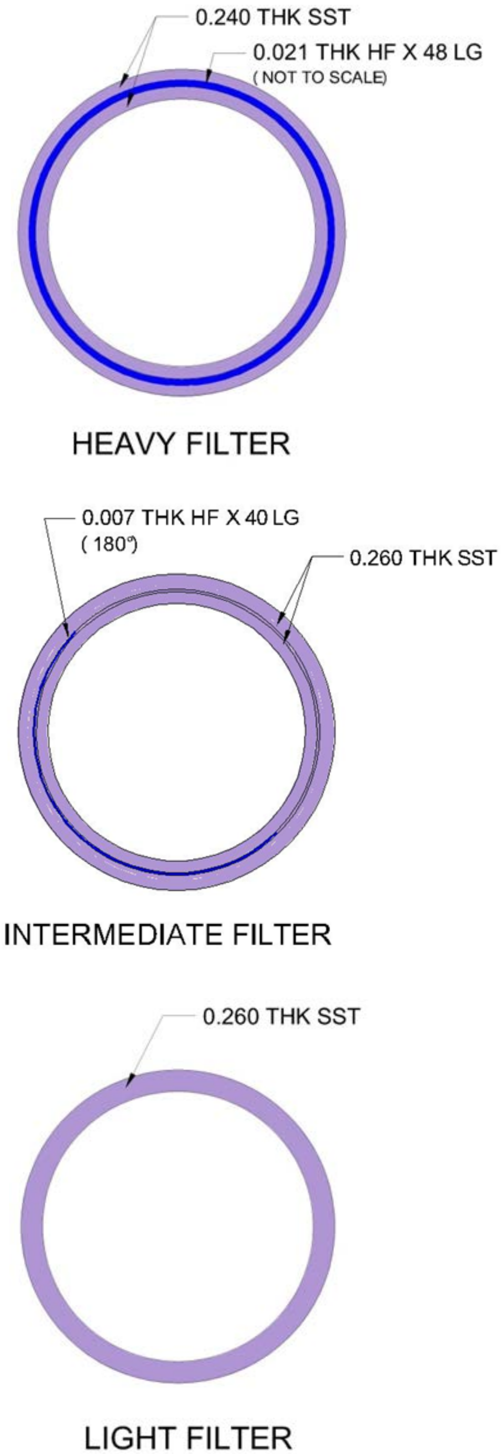

Fig. 10. AGR-5/6/7 neutron filters

VII. CONTROL AND MONITORING SYSTEMS

Because most of the AGR-3/4 irradiation was concurrent with the AGR-2 irradiation, a second temperature control system was needed. The new system has 14 temperature control channels (one for each capsule, one for the leadout, and an installed spare). The new system essentially is a duplicate version of the original AGR-1 system (Figure 11).

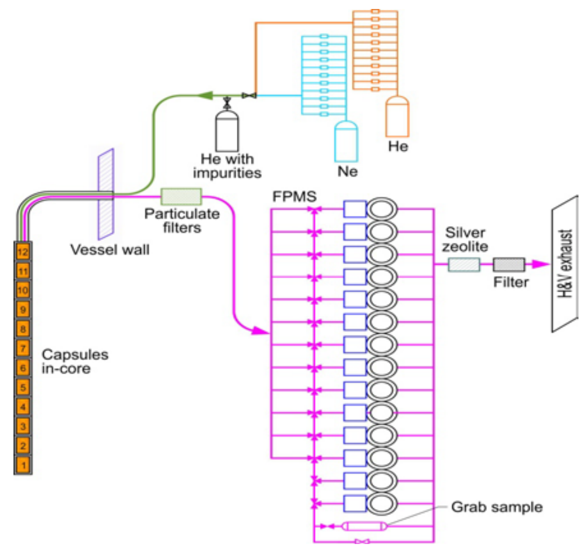

Fig. 11. AGR experiment gas flow path.

Each capsule has its own custom-blended gas supply and exhaust for independent temperature control and fission product monitoring. The desired temperatures in the experiment capsules were achieved by adjusting the mixture ratio of two different gases with opposing thermal conductivities to control heat transfer across the two insulating gas gaps between the heat source (i.e., fuel fissions and gamma heating of capsule materials) and the capsule wall that is in direct contact with the relatively cold ATR primary coolant (52ºC). Helium is used as the high (thermally) conductive gas and neon is used as the insulating gas. Neon (versus argon that can provide a wider temperature control band) is typically used in fuel irradiations such as the AGR experiments for the insulating gas to prevent activated argon gas from overwhelming the fission product monitors. Computer-controlled mass flow controllers are used to automatically blend the gases (based on feedback from experiment thermocouples) to control thermocouple temperatures, which are analytically coupled to the fuel specimen temperatures. A more detailed description of the AGR temperature control system design and functions can be found in Grover and Petti (2007).[3]

In order to minimize temperature changes and maintain temperature as constant as possible, the temperature control gas system provides a continuous flow to each specimen capsule. Monitoring this continuous gas flow for fission gases provides valuable information on fuel performance during irradiation. As indicated earlier, the AGR-3/4 test train contained 12 experiment capsules controlled by the 12 new temperature control channels discussed earlier. Therefore, the new fission product monitoring system installed for AGR-3/4 contains 12 primary monitors plus two spare monitors. As shown in Figure 11, the outlet gas from each capsule was routed to its individual fission product monitor and the gas flows can be rerouted to an online spare monitor if any of the primary monitors experience detector failure or other failures. The new monitors are duplicates of the original monitors that have performed exceptionally well on the AGR-1 and AGR-2 experiments. The new system has two online spare monitors; therefore, the ratio of spare monitors to prime monitors is the same as the previous systems (e.g., one spare for each six prime monitors). The new system also has the capability of re-routing the effluent of any capsule to either spare monitor to maximize the flexibility of the system. This same system will be used for AGR-5/6/7.

The fission product monitors consist of a high purity germanium spectrometer for identifying and quantifying the fission gas nuclides and a sodium iodide liquid scintillation gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides release timing. With the combination of a gross gamma detector and a spectrometer being continuously online, gross gamma detector results can be scanned quickly to determine which portions of the voluminous spectrometer data need to be closely scrutinized. Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release-to-birth ratio (with uncertainties) of the fission gases being detected. Determination of the release-to-birth ratios can establish whether a TRISO fuel coating failure has occurred or there is uranium contamination on the outside surface of the fuel particles. These details can be very important in the testing of relatively small TRISO particle fuel lots, where the particle failures need to be tallied very accurately to support statistical qualification of the fuel or development of improved fuel performance for an HGTR. The fission product monitoring system was designed and response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure. A more comprehensive description of the AGR fission product monitoring system design and functions can be found in Grover and Petti (2007).[3]

VIII. REQUIREMENTS SUMMARY TABLES

Table I. AGR-5/6/7 irradiation test specifications.

Parameter	AGR-5/6 Specification	AGR-7 Specification
Instantaneous peak temperature for each capsule (°C)	≤1800	≤1800
Time average temperature distribution goals (°C)	≥600 and <900 for about 30% of fuel ≥900 and <1050 for about 30% of fuel ≥1050 and <1250 for about 30% of fuel ≥1250 and <1350 for about 10% of fuel	Not specified
Time average, peak temperature goal (°C) (for one element)	1350 ± 50	1500 ± 50
Time average, minimum temperature goal (°C)	≤700	Not specified
Minimum compact average burnup (% FIMA)	>6 for all compacts	>6 for all compacts
Maximum fuel compact average burnup (% FIMA)	>18 for at least one compact	>18 for at least one compact
Maximum fuel compact fast neutron fluence (n/m^2, E > 0.18 MeV)	$\geq 5.0 \times 10^{25}$ for at least one compact and $\leq 7.5 \times 10^{25}$ for all compacts	$\geq 5.0 \times 10^{25}$ for at least one compact and $\leq 7.5 \times 10^{25}$ for all compacts
Minimum fuel compact fast neutron fluence (n/m^2, E > 0.18 MeV)	$> 1.5 \times 10^{25}$	$> 1.5 \times 10^{25}$
Instantaneous peak power per particle (mW/particle)	≤400	≤400

Table II. AGR-5/6/7 temperature distributions.

AGR-5/6	
Desired fraction of particles per temperature range	Number of Particles Based on 500,000 total
30% <900°C	150,000
30% 900°C - 1050°C	150,000
30% 1050°C - 1250°C	150,000
10% 1250°C - 1350°C	50,000
Total	500,000
AGR-7	
Temperature Range	Minimum Number of Particles
1350°C - 1500°C	50,000

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